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Numerical study of bird flu infection process within a poultry farm with consideration of age structure

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Numerical study of bird flu infection process within a poultry farm with consideration of age structure

Tertia Delia Nova[a],*, Masaji Watanabe[b]

[a]Faculty of Animal Science, Andalas University, Padang, West Sumatra, Indonesia

E-mail address: tertiaunand@ymail.com

[b]Graduate School of Environmental and Life Science, Okayama University, Okayama, Japan

E-mail address: watanabe@ems.okayama-u.ac.jp

ABSTRACT

Bird flu infection processes within a poultry farm was studied numerically. A mathematical model proposed in a previous study was reformulated with consideration of an age structure. The mathematical model for a susceptible population and an infected population is described. Numerical results show that essential factors for security against bird flu are vaccination and removal of infected bird.

Keywords: bird flu, mathematical modeling, numerical simulation, age structure

1. INTRODUCTION

The loss of domestic birds due to bird flu has been a serious threat to poultry farmers ever since the disease prevailed worldwide in 2003. The source of the disease is an influenza virus H5N1, and it is carried by wild birds. Forms of infection with H5N1 is classified into low pathogenic form and highly pathogenic form. The infection with the highly pathogenic form spreads rapidly over a poultry farm and subject domestic birds to serious symptoms that eventually lead to death. Even if infection of one bird with H5N1 is detected, all the birds in the farm are subjected to culling. Thus losses due to bird flu caused substantial damage to the poultry industry.

A bird flu infection process within a poultry farm involves the source of disease (influenza virus), the host (poultry), and the medium (environment). Once bird flu attacks a poultry farm, some birds die at the early stage of infection, and some others live longer. Regardless of being alive or dead, infected birds remain being sources of infection, unless they are completely removed. Those factors were incorporated in formulation of mathematical model for populations of susceptible birds and infected birds [2]. The mathematical model was reformulated for addition of virus concentration to unknowns [3, 4, 5, 6]. Those studies show that proper vaccination and removal of infected birds are essential for security of a poultry farm against an outbreak of bird flu.

This study revisited bird flu infection processes within a poultry farm. In particular, age structure of domestic birds was taken into consideration. In an egg production process, entire population of domestic birds is maintained at the manageable capacity by supply of six-month old birds for vacancies created by removal of thirty-month old birds. In the following sections, a mathematical model is described, numerical techniques are illustrated, and numerical results are presented.

2. Modeling bird flu infection process with age structure of population

When bird flu intrudes into a poultry farm, domestic birds are divided into the class of healthy birds susceptible to infection and the class of infected birds. The *SI* model was proposed in studies of the population of susceptible individuals and the population of infected individuals [7]. The *SI* model is inappropriate for susceptible and infected populations of poultry farms, where the entire population is regulated. In a production process of a poultry farm, the entire population of domestic birds is kept at the capacity of the farm with supply of new birds for vacancies. Let $X(t)$ and $Y(t)$ denote the population of susceptible birds and the population of infected birds, respectively, at time t, and Let c be the capacity of the farm. Then the rate of supply of new birds is $a[c-(X(t)+Y(t))]$, where a is the rate of supply. The infected birds do not recover from the disease. Some birds die at the early stage of infection and others stay alive longer. Regardless of being alive or dead, infected birds are virus carriers unless they are removed from the population. The removal rate of infected birds is proportional to their population, and it is expressed by $-mY(t)$, where m is the removal rate. The following system (1), (2) was proposed [1].

$$\frac{dX}{dt} = a[c-(X+Y)] - \omega XY, \tag{1}$$

$$\frac{dY}{dt} = \omega XY - mY, \tag{2}$$

In this study, age structure was considered in formulation of susceptible birds and infected birds. In an egg production processes, entire population of domestic birds is maintained at the capacity of the farm by supply of six-month old birds for vacancies created by removal of thirty-month old birds. Suppose that domestic birds in a poultry farm is distributed over an age interval $[q,s]$. Here q [mth] is the age of fresh birds that are supplied for vacancies, and s [mth] is the age of birds that are removed from the egg production process. Denote by $X(a,t)$ and $Y(a,t)$ the numbers of susceptible birds and infected birds of age a [mth] at time t [mth], respectively. The rate of infection of susceptible birds of age a at time t is proportional to the product of $X(a,t)$ and the total number of infected birds $\int_q^s Y(a,t)da$, and the removal rate of infected birds of age is at time t is proportional to $Y(a,t)$

The following system of equations are proposed.

$$\frac{\partial X}{\partial t} + \frac{\partial X}{\partial a} = -\omega X \int_q^s Y(a,t)da, \tag{3}$$

$$\frac{\partial Y}{\partial t} = \omega X \int_q^s Y(a,t)da - mY, \tag{4}$$

System of equations (3), (4) is associated with the initial conditions,

$$X(a,0) = X_0(a), \quad Y(a,0) = Y_0(a). \tag{5}$$

Vacancies are replaced with supply of susceptible birds of age q. So the system of equations (3), (4) is associated with the boundary condition,

$$X(q,t) = c - \int_q^s [X(a,t) + Y(a,t)]da. \tag{6}$$

3. Stationary state population of susceptible birds and infected birds

Stationary points of system (1), (2) are constant solutions. For fixed but arbitrary positive values of *a*, *c*, ω, and *m*, there are two stationary points,

$$(X,Y) = (c,0). \tag{7}$$

and

$$(X,Y) = \left(\frac{m}{\omega}, \frac{a(c\omega - m)}{\omega(a+m)}\right). \tag{8}$$

The stationary point (10) corresponds to the state of no infection, in which no bird is infected. The stationary point (11) corresponds to an endemic state in which a part of population is always infected. The stationary (8) is practical provided its *y* component is non-negative, that is,

$$c\omega - m > 0, \tag{9}$$

while it is unpractical for $c\omega - m < 0$. The stationary points (8) and (9) coincide for $c\omega - m = 0$. When the stationary point (8) is asymptotically stable, the state returns to it after disturbance due to intrusion of bird flu. The stationary point (9) is unstable under the condition (10), and that it is asymptotically stable for $c\omega - m < 0$. The stationary point (9) is asymptotically stable under the condition (10). It is unstable for $c\omega - m < 0$ [2].

The initial boundary value problem (3) – (6) has a constant solution. Suppose that $X(a,t) = \xi$, $Y(a,t) = \eta$ $(q \le a \le s, t \ge 0)$ is a constant solution of the system (3) – (6), where ξ and η are nonnegative constants.
Equations (3) and (4) lead to

$$-\omega(s-q)\xi\eta = 0, \tag{10}$$

$$[\omega(s-q)\xi - m]\eta = 0. \tag{11}$$

System of equations (10), (11) implies $\eta = 0$, and the boundary condition (6) leads to

$$\xi = c - (s-q)\xi. \tag{12}$$

The solution of equation (12) is $\xi = c/(1+s-q)$, and

$$(X,Y) = \left(\frac{c}{1+s-q}, 0\right) \tag{13}$$

is a constant solution of the initial boundary value problem (3) – (6).

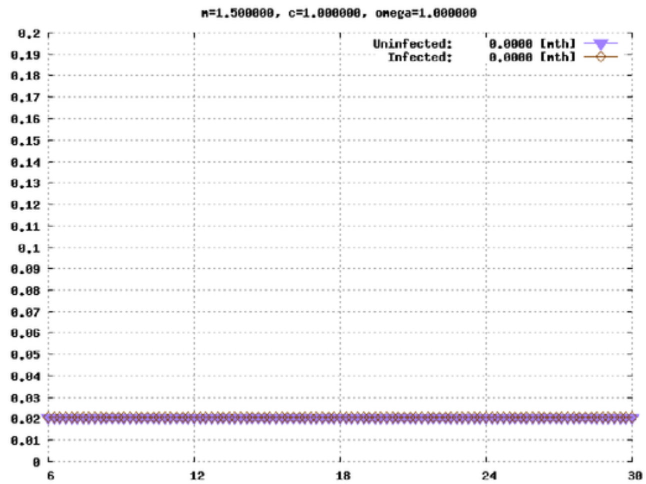

Figure 1: Numerical solution for $q = 6.0$ $s = 30.0$, $c = 1.0$, $\omega = 1.0$, and $m = 1.5$. The figure shows the numerical solution of the initial boundary value problem (3) – (6) for $t = 0.0$ [mth].

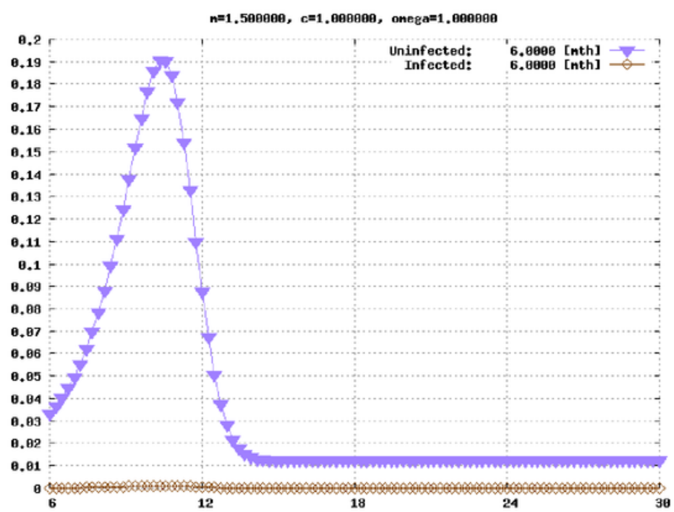

Figure 2: Numerical solution for $q = 6.0$ $s = 30.0$, $c = 1.0$, $\omega = 1.0$, and $m = 1.5$. The figure shows the numerical solution of the initial boundary value problem (3) – (6) for $t = 6.0$ [mth].

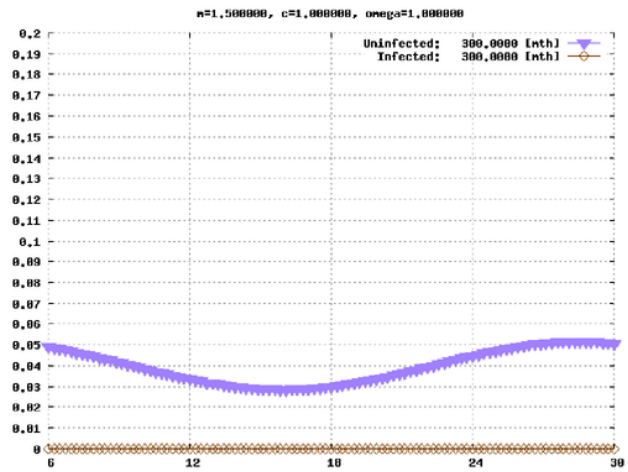

Figure 3: Numerical solution for $q = 6.0$ $s = 30.0$, $c = 1.0$, $\omega = 1.0$, and $m = 1.5$. The figure shows the numerical solution of the initial boundary value problem (3) – (6) for $t = 300.0$ [mth].

4. Numerical solution of equations for susceptible population and infected population

The initial boundary value problem (3) – (6) was analyzed numerically for $q = 6.0$ $s = 30.0$, $c = 1.0$, and $\omega = 1.0$. Figures 1 – 3 show profiles of a numerical solution for $m = 1.5$. Those figures indicate that the solution approaches the constant solution (13). Figures 4 – 6 show profiles of a numerical solution for $m = 0.5$. Those figure indicate that the solution quickly approaches a non-constant time-independent solution.

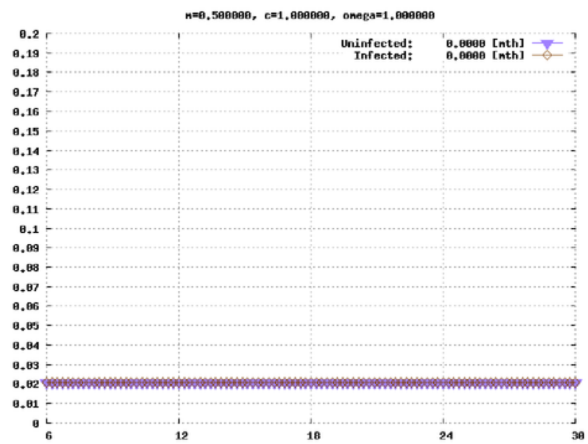

Figure 4: Numerical solution for $q=6.0$ $s=30.0$, $c=1.0$, $\omega=1.0$, and $m=0.5$. The figure shows the numerical solution of the initial boundary value problem (3) – (6) for $t=0.0$ [mth].

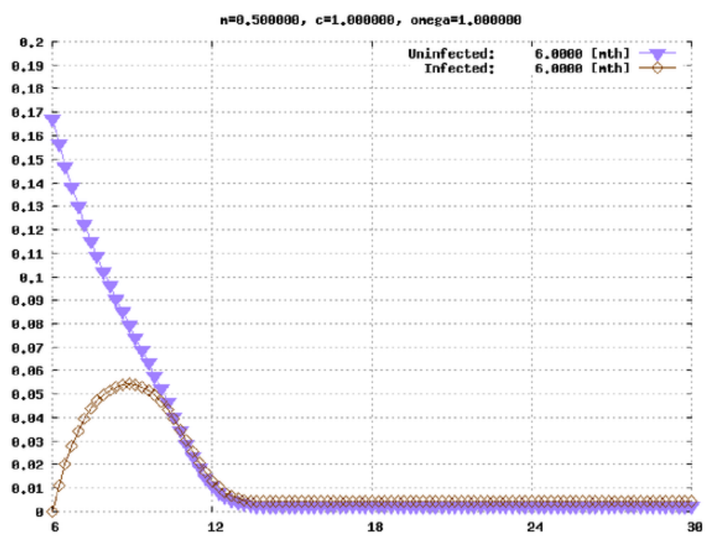

Figure 5: Numerical solution for $q=6.0$ $s=30.0$, $c=1.0$, $\omega=1.0$, and $m=0.5$. The figure shows the numerical solution of the initial boundary value problem (3) – (6) for $t=6.0$ [mth].

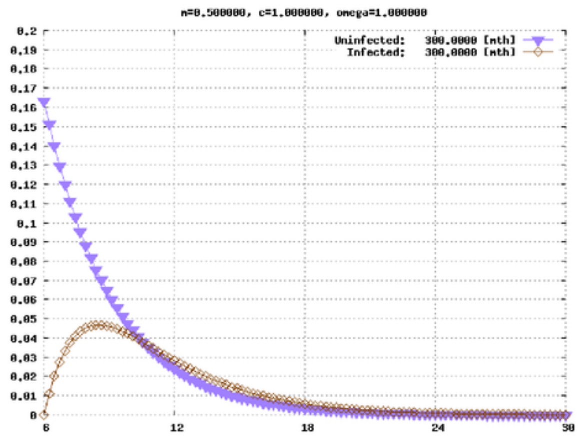

Figure 6: Numerical solution for $q = 6.0$ $s = 30.0$, $c = 1.0$, $\omega = 1.0$, and $m = 0.5$. The figure shows the numerical solution of the initial boundary value problem (3) – (6) for $t = 300.0$ [mth].

5. DISCUSSION

The previous studies based on a mathematical model (1), (2) showed that the stationary solution corresponding to the infection free state was asymptotically stable while the other stationary points was unpractical. In this study, age structure was incorporated in formulation, Nnumerical solutions of the initial-boundary value problem (3) - (4) also showed that the constant solution corresponding to the infection free state was asymptotically stable for a large value of the removal rate m. Numerical results indicated that the infection free state was unstable when another non-constant time independent solution was asymptotically stable.

Those results suggests the condition $c\omega - m < 0$ to be a possible criterion for stability of the infection free state. This shows that removal of infected birds is essential for security of a poultry farm against a bird flu outbreak. The vaccination reduces the value of ω. This show that proper vaccination is also an important factor for security against a bird flu outbreak.

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